IDA DOCUMENT D-1059

SMOKE PLUMES FROM KUWAITI OIL FIRES AS ATMOSPHERIC EXPERIMENT OF OPPORTUNITY: AN EARLY LOOK

Ernest Bauer

October 1991

Prepared for
Strategic Defense Initiative Organization

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INSTITUTE FOR DEFENSE ANALYSES
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1991	Final--March - October 1991

4. TITLE AND SUBTITLE

Smoke Plumes From Kuwaiti Oil Fires as Atmospheric Experiment of Opportunity: An Early Look

5. FUNDING NUMBERS

C - MDA 903 89 C 0003

T - T-R2-597.12

6. AUTHOR(S)

Ernest Bauer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Institute for Defense Analyses
1801 N. Beauregard St.
Alexandria, VA 22311-1772

8. PERFORMING ORGANIZATION REPORT NUMBER

IDA Document D-1059

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Strategic Defense Initiative Organization
The Pentagon
Washington, DC 20301-7100

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This document sets in context the smoke plume phenomenology associated with the large number of oil fires lit by the Iraqi military in Kuwait in February 1991, and which are probably the worst man-made air pollution event in human history. Based on the simple phenomenology given here, and considered an unfortunate "experiment of opportunity," the question is raised of what actions should be taken, and what one can hope to learn from these events. From the standpoint of SDIO, most of the basic physical elements of the fire and smoke phenomenology appear to be understood although there are some new effects and the initial quantitative predictions of the experts appear to differ significantly from the results of the detailed measurements. Many observations have been made. They require analysis followed by review and publication before being incorporated in the DOD integrated phenomenology models. This document represents an early look at the smoke plumes before most of the observations have been analyzed, reviewed, and published; its main function is to raise questions that should be addressed more carefully later.

14. SUBJECT TERMS

oil fires, air pollution, smoke

15. NUMBER OF PAGES

47

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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Task T-R2-597.12

PREFACE

This document was prepared between March and June 1991, and was reviewed between July and September by five individuals, three of whom have been much more intimately involved with the measurements of the Kuwaiti oil fire plumes than I. Thus their comments--which are presented in Section 7--have enabled me to update and change some significant conclusions. Nevertheless, the reader should realize that this is a status report in a very rapidly evolving field in which detailed experimental results are now just beginning to come in. Thus, for example, at the American Geophysical Union Meeting in San Francisco in December 1991 there will be several sessions of contributed papers, possibly 50 in all, and a number of different technical meetings will cover this area during the next several years.

In preparing the paper, I have received inputs from Art Aikin and Bob Fraser, NASA/GSFC; Frank Albini, SAIC; Jim Angell, Diane Gaffen, Nick Heffter, and Bruce Hicks, NOAA/ARL; David Auton, Mohammad Owais, and Leon Wittwer, DNA; Stan Grigsby, NRL/BDC; Irv Kofsky, Photometrics, Inc.; Mike Matson, NOAA/NESDIS; David Pitts, NASA/MSC; Rich Small, Pacific-Sierra Research; and Ed Tomlinson, North American Weather Consultants.

I wish particularly to thank the reviewers: Frank Albini, SAIC, Bohdan Balko, IDA/STD, John Cockayne, SAIC, Paul Janota, TASC, and Rich Small, Pacific-Sierra Research, for their detailed and thoughtful comments, which have improved the paper significantly.

This work was done under Task T-R2-597.12 (POET) in response to a request from LTC C.B. Johnson, SDIO/TDS.

ABSTRACT

This document sets in context the smoke plume phenomenology associated with the large number of oil fires lit by the Iraqi military in Kuwait in February 1991, and which are probably the worst man-made air pollution event in human history. Based on the simple phenomenology given here, and considered an unfortunate "experiment of opportunity," the question is raised of what actions should be taken, and what one can hope to learn from these events. From the standpoint of SDIO, most of the basic physical elements of the fire and smoke phenomenology appear to be understood although there are some new effects and the initial quantitative predictions of the experts appear to differ significantly from the results of the detailed measurements. Many observations have been made. They require analysis followed by review and publication before being incorporated in the DOD integrated phenomenology models. This document represents an early look at the smoke plumes before most of the observations have been analyzed, reviewed, and published; its main function is to raise questions that should be addressed more carefully later.

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GLOSSARY

AVHRR	advanced very high resolution radiometer
FF	forest fire
GOES	geo-stationary operational environment satellite
KOF	Kuwaiti oil fire
LWIR	long wave infrared
MWIR	medium wave infrared
NOAA/ARL	National Oceanic and Atmospheric Administration/Air Resource Laboratory
PSR	Pacific-Sierra Research
SB	slash and burn
SDIO	Strategic Defense Initiative Organization

SUMMARY

This document has been prepared as part of the Operational Environments work for SDIO, which is focused on assuring that critical environments (natural, nuclear, kinetic debris, etc.) are incorporated appropriately in engagement models for system operational simulation.

The Kuwaiti oil fires of 1991 are a unique event. Some 730 oil wells were set on fire by the Iraqi military in February 1991. This is apparently the worst man-made air pollution event in history, and it is to be hoped that such a phenomenon will never occur again. It is appropriate to ask whether the smoke plumes of these fires are of significance to SDIO or to some other DOD functions. Before one can ask this question, one needs a simple description of the phenomenology of the smoke plumes for context, and that is provided here. We make a simple estimate of the scale of the fires and of the smoke, and ask for how long a time one may expect to be able to track the mesoscale air mass containing the smoke by using overhead or other surveillance.

First let us ask how big an event this is. Table S-1 gives a simple characterization of a number of large fires in terms of the rate of combustion of fuel and of the injection rate of smoke into the atmosphere. While none of the numerical values can be relied upon to within a factor better than 3-10, it is clear that the Kuwaiti oil fires are a major disaster, much larger (because of its longer duration) than item FF (forest fire) of Table S-1, a 10^6 ha (2.5 million acre) forest fire, which is an event that tends to occur in Siberia or in Northern Canada once every few years. The biggest recorded forest fire, the conflagration of Siberia in 1915, was an order of magnitude larger than FF; the August 1988 forest fires in Yellowstone affected some 700,000 acres (280,000 ha).

Because of the large heating from each of the Kuwaiti oil fires and because of the low stability in the lower atmosphere, a large fraction of the smoke will be injected into the free troposphere, above the planetary boundary layer, and thus will mix into a mesoscale air mass which can be followed for times of several days. (Such an air mass retains its integrity for perhaps 3-10 days on the average, and because of this relatively short duration no major climatic effect is to be expected.) The total amount of smoke as well as its optical

properties depend on whether the smoke is largely "gray"--i.e., soot--or "white," if significant amounts of water (largely transported upward by atmospheric convection induced by the fires) condenses on the ambient aerosol/dust and soot particles as cloud condensation nuclei. The extinction of the signals to various sensors would be different in these two cases, and indeed conditions are highly variable and complex, with a varying mixture of black and white smoke as well as unburned oil droplets in an inhomogeneous atmospheric medium, with varying wind fields, temperature, and turbulence.

Table S-1. Tentative Estimates for Smoke Generation by Large Fires

Fire	Fuel Burned (tons)	Time of burning (days)	Smoke Fraction	Smoke Generation Rate (tons/day)
15. Lynn, MA, urban	200,000; "wood"	2	3%	3000
16. Anaheim, CA, brush	500,000; "wood"	7	3%	2200
18. Tacoa, Venezuela	40,000; oil	3	5%	670
19. Winchester, VA, tires	200,000, rubber	90	10%	220
SB. Slash and burn, 1,000 ha/day	10,000/day; wood	1	3%	300
FF. 10^6 ha boreal forest	2×10^7; "wood"	30	3%	20,000
KO. Kuwait Oil Fires, 3/91	0.9×10^6/day; oil	~ 1 year	5%(?)	45,000

NOTE: 1. The numbers associated with each fire refer to Table 2, which is a listing of large fires of various kinds.

2. The largest recorded series of forest fires, in Siberia in 1915, was about 14 times larger than FF.

3. R. Small, PSR, suggests a smoke generation rate of 15,000 tons/day for Kuwait Oil Fires (pvt. comm., 13 March), while TASC (Chase et al., 1991) use a smoke generation rate of 67,000 tons/day. In this context, I consider a factor of 3 to be "one-sigma" agreement.

A simple discussion of the various interacting physical factors is given in the text together with limiting numerical estimates based on different simple sets of assumptions.

Based on the simple phenomenology given here, and considered an unfortunate "experiment of opportunity," the questions raised in the concluding section of the document are: What can one hope to learn from these events, and what action should be taken right now?

From the standpoint of SDIO, most of the basic physical elements of the fire and smoke phenomenology appear to be understood, although there are some new effects and

the initial quantitative predictions of the experts appear to differ significantly from the results of the detailed measurements. Many observations have been made; they require analysis followed by review and publication before being incorporated in the DOD integrated phenomenology models. Apart from supporting this data analysis, DOD/SDIO should use the new observations to determine how successful the DOD integrated phenomenology models are in describing the total problem involving many interacting fires rather than a single fire.

This document represents an early look at the smoke plumes before most of the observations have been analyzed, reviewed, and published. Thus its main function is to raise questions that should be addressed more carefully once the initial observations are in hand.

1.0 INTRODUCTION

The Kuwaiti oil fires represent an ecological and economic disaster for the State of Kuwait. As long as the fires burn, they are a major source of air pollution for the region. This being so, one may ask what use one can make of this "atmospheric experiment of opportunity" to study the perturbed atmosphere.

First let us ask how big an event this is. Table 1 gives a simple characterization of a number of large fires in terms of the rate of combustion of fuel, and of the injection rate of smoke into the atmosphere. While none of the numerical values can be relied upon to within a factor better than 3-10, it is clear that the Kuwaiti oil fires are a major disaster. The rate of smoke generation is on the scale of item FF of Table 1, a 10^6 ha (2.5 million acre) forest fire, an event which tends to occur in Siberia or in Northern Canada once every few years. [For comparison, the August 1988 Yellowstone forest fires affected some 700,000 acres (280,000 ha), a number quoted by Yellowstone National Park Public Relations Officer; see also Rothermel, 1991.] The Kuwaiti oil fires are now expected to last until the end of 1991, as compared to roughly a month for a series of large forest fires. The biggest recorded forest fire, the conflagration of Siberia in 1915, was an order of magnitude larger than the canonical 2.5 million acre fire. The Kuwaiti oil fires are probably the worst man-made air pollution event in human history (cf. Horgan, 1991).

Next it is appropriate to summarize our present understanding of the Kuwaiti oil fires. From the news media and from other eyewitness reports it is clear that conditions are highly variable on a day-by-day basis, and not always well known.[1] As of April - June, flames were burning up to 50 meters high, and many of the plumes rose above the boundary layer, into the free troposphere. Some of the smoke plumes were grey or black, some were white (mainly water, both from combustion and from moist surface air entrained by convection, possibly also from underground water penetration into the oil field; much of this moisture condenses in the cold upper atmosphere, partly from salt which

[1] As of 15 June 1991, probably some 150-170 fires out of a reported 500-600 had been put out; the total daily loss of oil lies in the range 1.5-7 Mbbl; see Horgan, 1991, Marshall, 1991. By late September 1991 it appeared that there had originally been some 730 fires which were then being extinguished at an average rate of 5-6 per day, and it was projected that essentially all the fires would be out by the end of 1991.

is very common in aerosols in the Gulf region); some wells had been re-ignited to minimize the formation of pools of oil on the surface, some of which were 2 meters deep and extended over tens of km^2; see, e.g., Marshall, 1991. In addition to this, there were oil droplets from unburnable crude. Ambient meteorological conditions are variable; thus Fig.1A shows that on 5-8 April the wind was blowing towards the southwest, while Figs. 1B and 1C show that on 10-11 April the wind was turning, sending the smoke towards the east. The mean smoke layer over Kuwait lies at altitudes of 8,000-12,000 ft.

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FF. 10^6 ha boreal forest	*2×10^7; "wood"*	*30*	3%	*20,000*
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This document provides a synthesis of what I had learned to mid-June from analysis, from personal contacts, from the scientific literature, and from the news media.[2] Section 2 gives a brief discussion of some large historic fires, with more detail on many of the events shown in Table 1. Note that in general the largest forest fires are much larger than fires in urban or industrial regions which have a much higher economic value per unit

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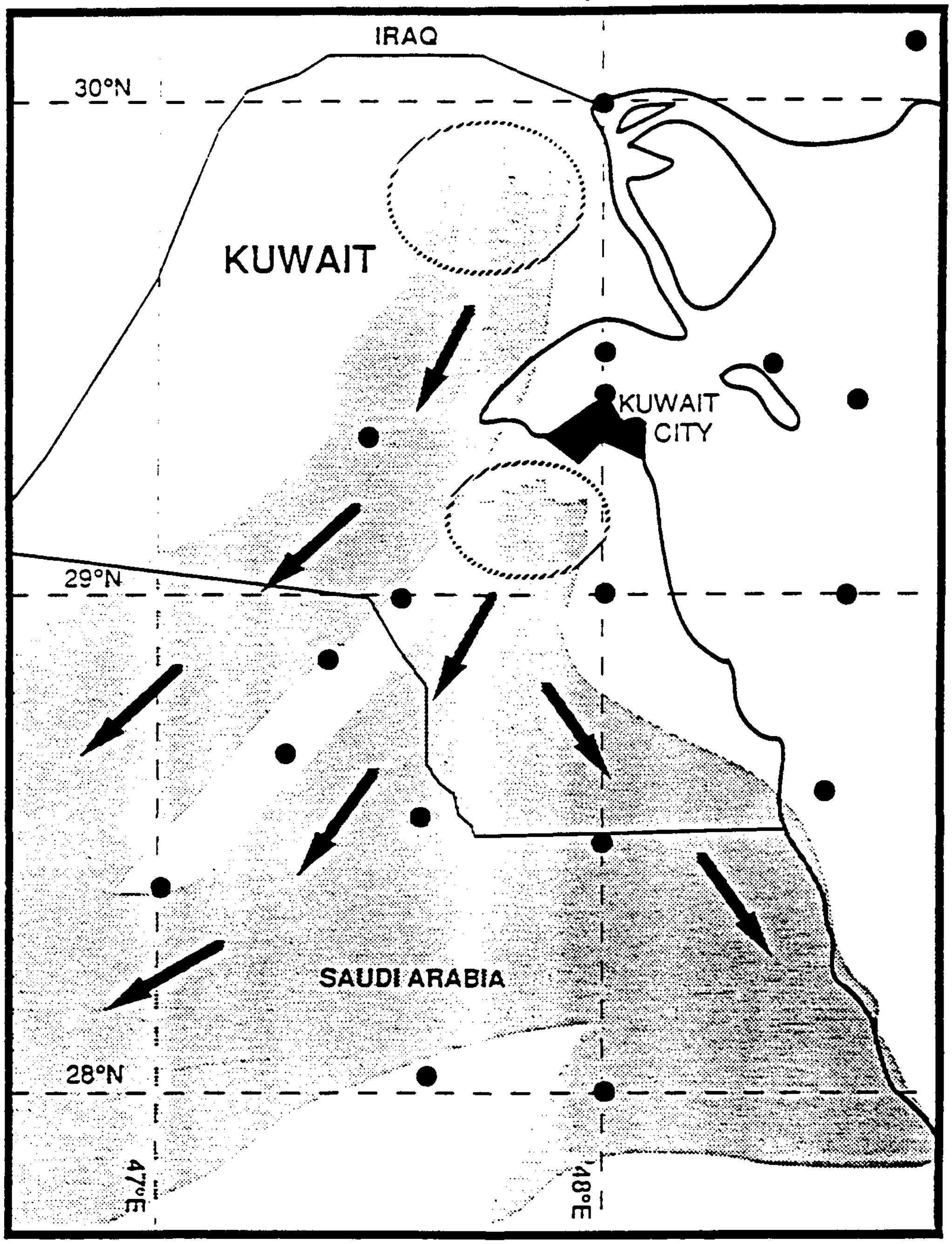
[2] *It has been revised extensively in mid-October 1991 to incorporate the reviewers' comments as well as* other information.

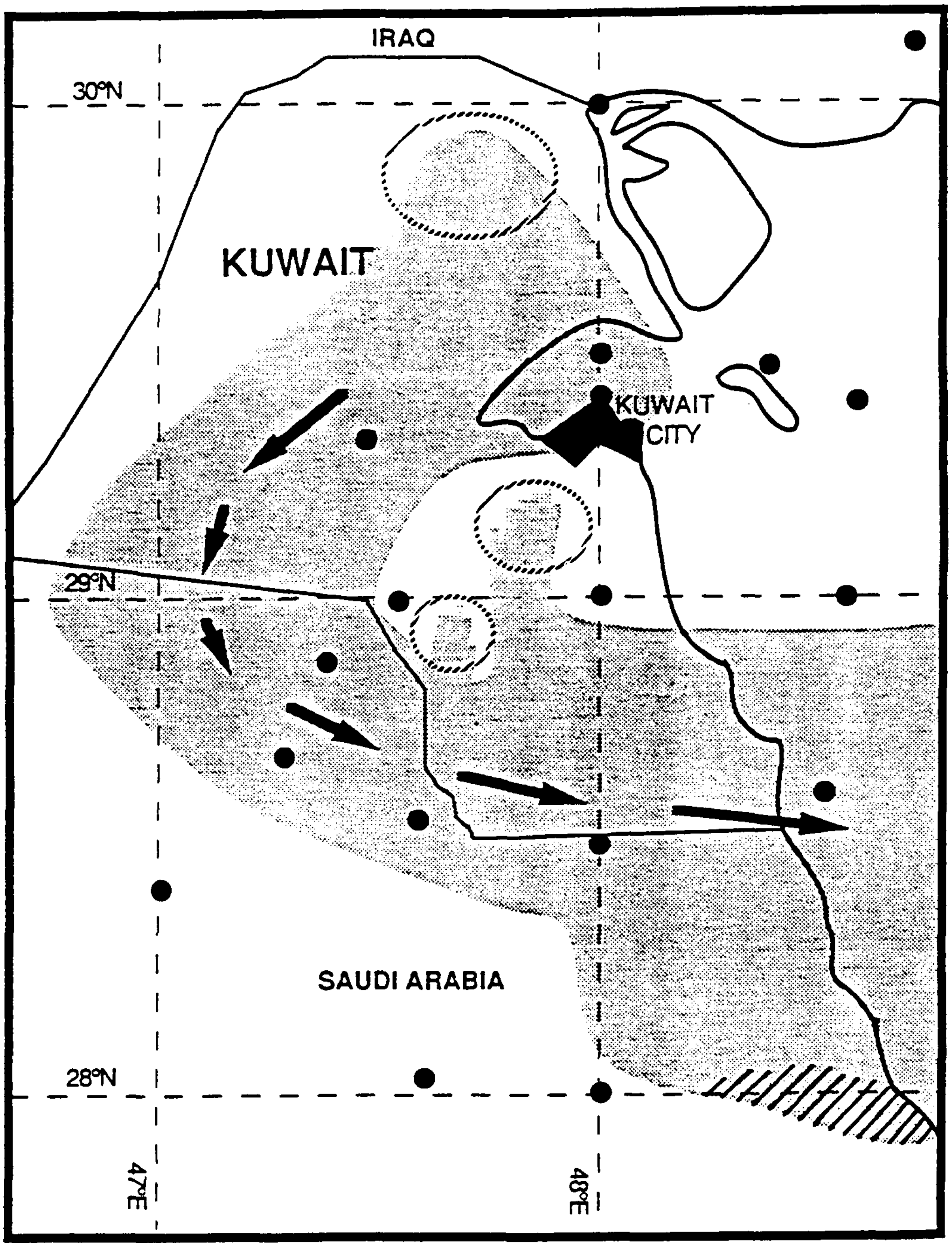


Legend

● = centerpoint of individual photograph

◌ = primary oil field source regions visible

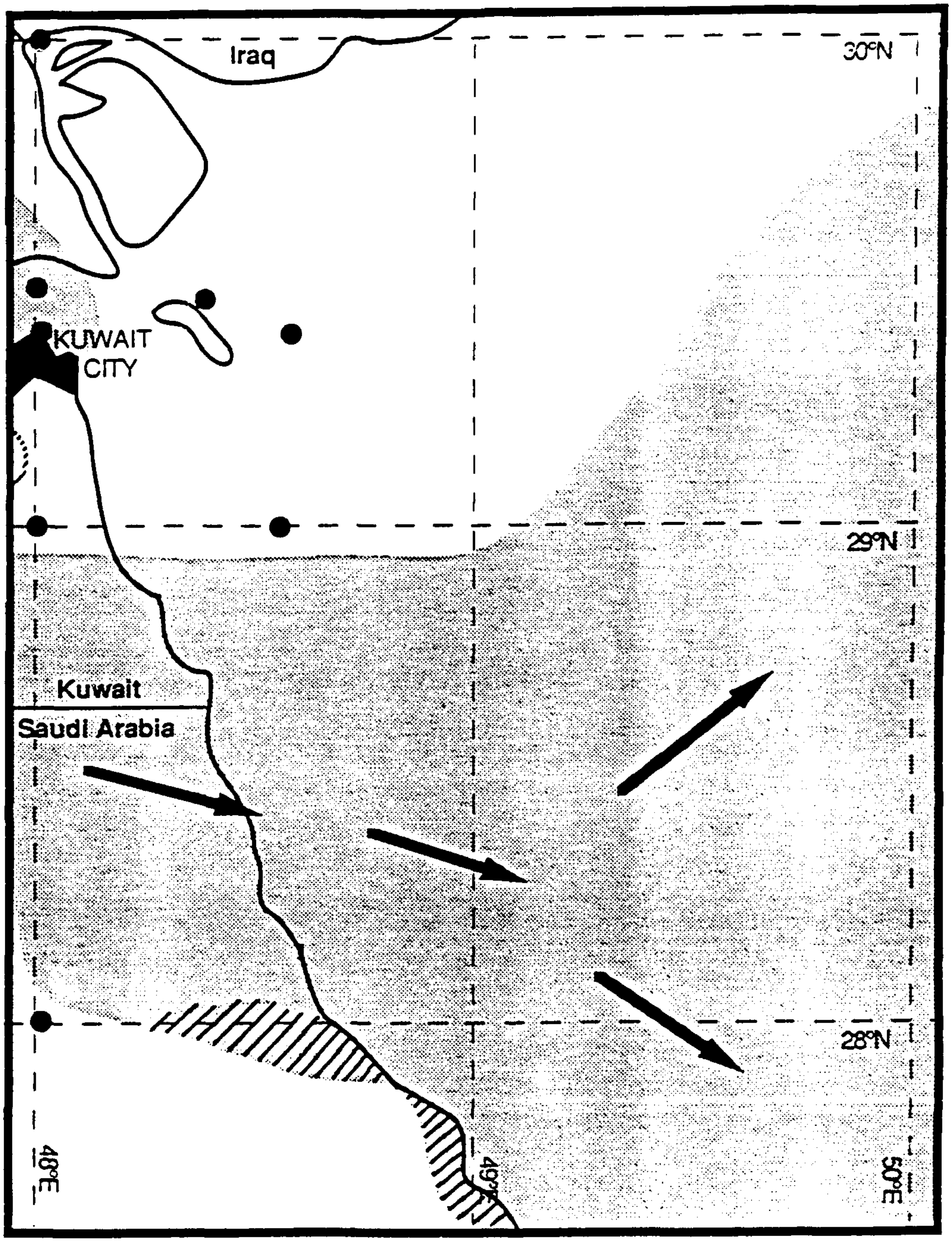
Figure 1A. Extent of Smoke from the Kuwaiti Oil Fires from Space Shuttle Photographs, 5-8 April 1991 (Source: Lulla and Helfert, 1991)



Legend

● = centerpoint of individual photograph
◌ = primary oil field source regions visible
▨ = interpretation in this area is equivocal

Figure 1B. Extent of Smoke from the Kuwaiti Oil Fires from Space Shuttle Photographs, 10-11 April 1991 (Source: Lulla and Helfert, 1991)



Legend

● = centerpoint of individual photograph
◌ = primary oil field source regions visible
/// = interpretation in this area is equivocal

Figure 1C. Extent of Smoke from the Kuwaiti Oil Fires from Space Shuttle Photographs, 10-11 April 1991 (Source: Lulla and Helfert, 1991)

area, and thus have much better fire surveillance and protection so that they are typically contained before they do an enormous amount of damage. Section 3 reviews fire phenomenology: energetics, combustion products, plume rise, and the issue of "black" vs. "white" smoke. Section 4 treats atmospheric motions on different scales of space and time. Section 5 discusses the optical obscuration due to smoke clouds, and Section 6 combines all these elements to set the Kuwait oil fires in context. Finally, Section 7 presents a discussion: What can one learn from the fires, and what critical observations make sense? This Section has been greatly modified and updated by incorporating the reviewers' comments which were prepared in the July-October time frame.

2.0 LARGE FIRES: A HISTORICAL OVERVIEW

Table 2 lists some large recent urban and industrial fires. It is presented here for orientation, to indicate the kind and magnitude of such fires, largely in the United States, over a 14-year period for which the data have been readily accessible to me. (Note that the Yellowstone Fires of 1988 were about one-tenth as big as the "canonical" 2.5 million acre fire (number quoted by Yellowstone National Park Public Relations Officer, see also Rothermel, 1991). At present the United States is so densely populated compared to Canada or the Soviet Union that the largest forest fires do not occur here because there are no longer such large unbroken forests. Table 3 shows the assumptions made in deriving the fuel equivalents for these fires and also for the items FF (forest fire) and SB (slash-and-burn agriculture[3]) of Table 1.

A crude estimate for the fire storm that occurred in Dresden, Germany, during World War II may be made as follows. Assume a fuel loading of 200 kg/m^2, mostly wood, with a heat of combustion of 1.9×10^7 joules/kg (see Table 3). If all the fuel in an area of 10 km^2 burns over a 24-hour period, this is 2×10^6 tons wood which would yield 60,000 tons smoke. These numbers are surely not accurate, but they may be compared with the other fires cited in Table 1 and Table 2.

Table 4 describes the Siberian 1915 fires which are the largest series of fires on record, and Table 5 and Fig. 2 describe the Canadian forest fires of September 1950. The Canadian 1950 event was studied particularly well because over the United States the smoke plume was in the 10-20 kft altitude range. At that time commercial aircraft flew at those altitudes, so we have good observational data on the smoke plume, which nowadays would not be available. There is evidence of detectable smoke some 5,000 miles downwind from the source, but no further.

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3 The global importance of slash-and-burn agriculture is not well known, but is probably quite large-- The Nature Conservancy quotes a deforestation rate of 10^7-2×10^7 ha/year, which is equivalent to more than 10 large boreal forest fires (or ~20% of the land area of W. Europe!).

Table 2. Historical List of Large Fires

Fire	Date	Location		Characteristics	Model	Fuel Equivalent (tonnes) Wood	Oil
1.	21-23 Jun 1970	Crescent City, IL		8 LPG cars derailed - entire downtown burned out	8 x 34,000 gal LPG + 25 city blocks	52,000	20,000
2.	22 Sep-2 Oct 1970	Laguna Mountains San Diego Co, CA	33°N;116°30'W	175,000 acres bush & timber, 385 buildings (mostly in Cleveland NF)	20 kg/m², 10% burns	1.4×10^6	5×10^5
3.	5 Dec 1970	Linden, NJ	40°38'N;74°15'W	Oil Refinery - $M50 damage	1 storage tank = 27,000 tonnes	70,000	27,000
4.	3 Feb 1971	Woodbine, GA	30°58'N;81°44'W	Chemical plant manufacturing flares - explosion and fire	?	?	?
5.	19 Oct 1971	Houston, TX	29°46'N;95°22'W	1 rail car of vinyl chloride burned			
6.	16 Dec 1972	Weirton, WV	40°24'N;80°35'W	Steel plant explosion and fire	?	?	?
7.	14-17 Oct 1973	Chelsea, MA	42°27'N;71°2'W	Town conflagration (> 100 square blocks). 300 buildings, mostly manufacturing and storage for flammable and combustible material	100 city blocks	200,000	77,000
8.	12 Feb 1974	Oneonta, NY	42°27'N;75°4'W	LPG train derailment (7 cars)	7 x 30,000 gal LPG	2,000	800
9.	9 Apr 1974	Tinicum TWP, PA		Oil tanker explosion (? truck)	20 tons oil	50	20
10.	22 Feb 1978	Waverly, TN	31°6'N;81°43'W	1 rail car LPG. 3-block area burned	34,000 gal LPG + 3 city blocks	7,500	2,900
11.	31 Jul 1979	Houston, TX	29°46'N;95°22'W	Apartment house complex burned (25-30 buildings)	10 city blocks	20,000	8,000
12.	1 Sep 1979	Deer Park, TX	20°43'N;95°8'W	Petroleum tank ship explosion	10,000 tons oil	26,000	10,000
13.	15 Aug 1980	Iwalei, HI		Gas tank overfilled; exploded and burned	1 tank	70,000	27,000
14.	21 Nov 1980	Las Vegas, NV	36°10'N;115°9'W	MGM Grand Hotel (not very big fire, lots of smoke)	< 10 city blocks	<20,000	<8,000
15.	28 Nov 1981	Lynn, MA	42°28'N;70°57'W	Urban conflagration	100 city blocks	200,000	77,000
16.	21 Apr 1982	Anaheim, CA	33°50'N;117°55'W	Brush fire and suburban residential area	10 sq mi @ 4 lb/sq ft	520,000	200,000
17.	21 Jun 1982	Falls TWP, PA	41°28'N;75°51'W	K-Mart distribution center and warehouse	?	?	?
18.	19-22 Dec 1982	Tacoa, Venezuela (10 mi NW of Caracas)	10°35N;78°10'W	2 fuel tanks at an electric power station burned	13,500,000 gal oil	110,000	40,000
19.	12:31am 31 Oct 1983	Winchester, VA	39°11N;78°10'W	9,000,000 tires burned	(1 tire equiv 50 lb oil)	530,000	200,000
20.	19 Nov 1984	San Juan Ixhuatepec, Mexico (10 mi N of Mexico City)	19°25N;99°10'W	LPG tank burned: 118,000 bbl storage tank and pipeline, 50,000-60,000 bbl/day	200,000 bbl LPG = 27,000 tonnes LPG	81,000	31,000

*Data provided by K.E. Isman, API and others. See sheet of assumptions for details.

Table 3. Assumptions on Fuel Loadings

1. All the designated fuel burns, except for the case of a forest fire.

2. <u>Heats of Combustion</u>

Material	Relative Values	J/kg	Kcal/g	BTU/lb
Wood	1	1.9×10^7	4.2	8,000
Petroleum	2.6	4.9×10^7	11.5	21,000
LPG	3.0	5.6×10^7	13.1	24,000

3. <u>Fuel Loading (Wood Equivalent).</u>

Old downtown	200 kg/m^2	40 lb/ft^2
Apartment house	200	40
Low-density suburb (Anaheim, CA)	20	4
Subarctic forest (10 % burns)	20	4

4. 1 city block = 100 m × 100 m = 2.5 acres

5. 1 automobile tire taken as equivalent to 50 lb oil, heat of combustion of rubber taken as heat of combustion of petroleum.

6. 1 tank car of 343,000 gallon = 100 tons

7. For a representative northern forest fire (Canada, Siberia, Alaska) with a fuel loading of 20 kg/m^2 of which 10% burns, a 25,000-acre burn corresponds to 20,000 tons of wood (energy--but not smoke--equivalent of 7,700 tons of oil). A 1-million-acre burn corresponds to 800,000 tons of wood or 310,000 tons of oil.

Table 4. Forest Fire Conflagrations in Siberia, 1915
(Source: D.E. Ward, USFS, from Shostakovitch, 1925)

• Forest fires burned unimpeded from May to September.			
• Covered 140,000 km^2, equal to about one-third of western Europe.			
• The fires were mostly crown fires and then burned the peat up to 2 meters deep.*			
• Smoke continuity lasted for 51 days.			
Type 1 smoke: Continuous smoke, objects not perceptible at 100 meters			(2,600,000 km^2)
Type 2 smoke: Nothing to be seen at a distance of 25-100 meters			(2,200,000 km^2)
Type 3 smoke: Nothing to be seen at a distance of 4-25 meters			(1,800,000 km^2)
• Visual range:	100 m	corresponds to a smoke loading of	10,000 $\mu g/m^3$
	25 m	corresponds to a smoke loading of	47,000 $\mu g/m^3$
	4 m	corresponds to a smoke loading of	260,000 $\mu g/m^3$
• Rainfall: On 30 July a very heavy smoke occurred in connection with a few drops of rain. Smoke became so dense that at 3 p.m., day changed to night.			
• Effects: Grass and hay were covered with soot with a smoky smell and bitter taste, which made cattle sick.			
• In July 1915, 85% of normal sunshine was received, and in August, 65% of normal.			

* A 2-meter depth of peat is equivalent to 2 ton/m^2 planform area (assuming a density of 1 g/cm^3), or 20 kt/ha, which is very much more than flaming combustion would consume. This could correspond to an absolutely horrendous fire (which of course this was). We appear to have no data to improve on these crude estimates.

Table 5. Canadian Forest Fires, September 1950
(Source: Smith, 1950, Wexler, 1950)

• Warm, dry air mass (high potential temperature Θ) over Western Canada in September 1950, started about 100 forest fires.
• Smoke plume observed over Eastern U.S. and over Europe: - Plume seen, sometimes reported just as cloud - Blue Sun and Blue Moon reported - Odor of burning paper reported by aircrews - No cooling reported
• Chronology: - 22 September, plume moves from B.C., Alberta - 24 September, observed over Eastern U.S. at 10,000 to 15,000 ft - 26 September, reported over U.K. at 30,000 to 38,000 ft - 27 September, reported over Europe (ground observations) - 29-30 September, reported over Gibraltar, Malta (ground observations)
• Smoke plume/cloud appeared to follow isentropes, not isobars. High Θ eventually goes to tropopause region. Material may have gone down in passage to Eastern U.S., then risen in transport to Europe.
• Air mass typically has 1-to-2-week lifetime, little goes into the stratosphere.

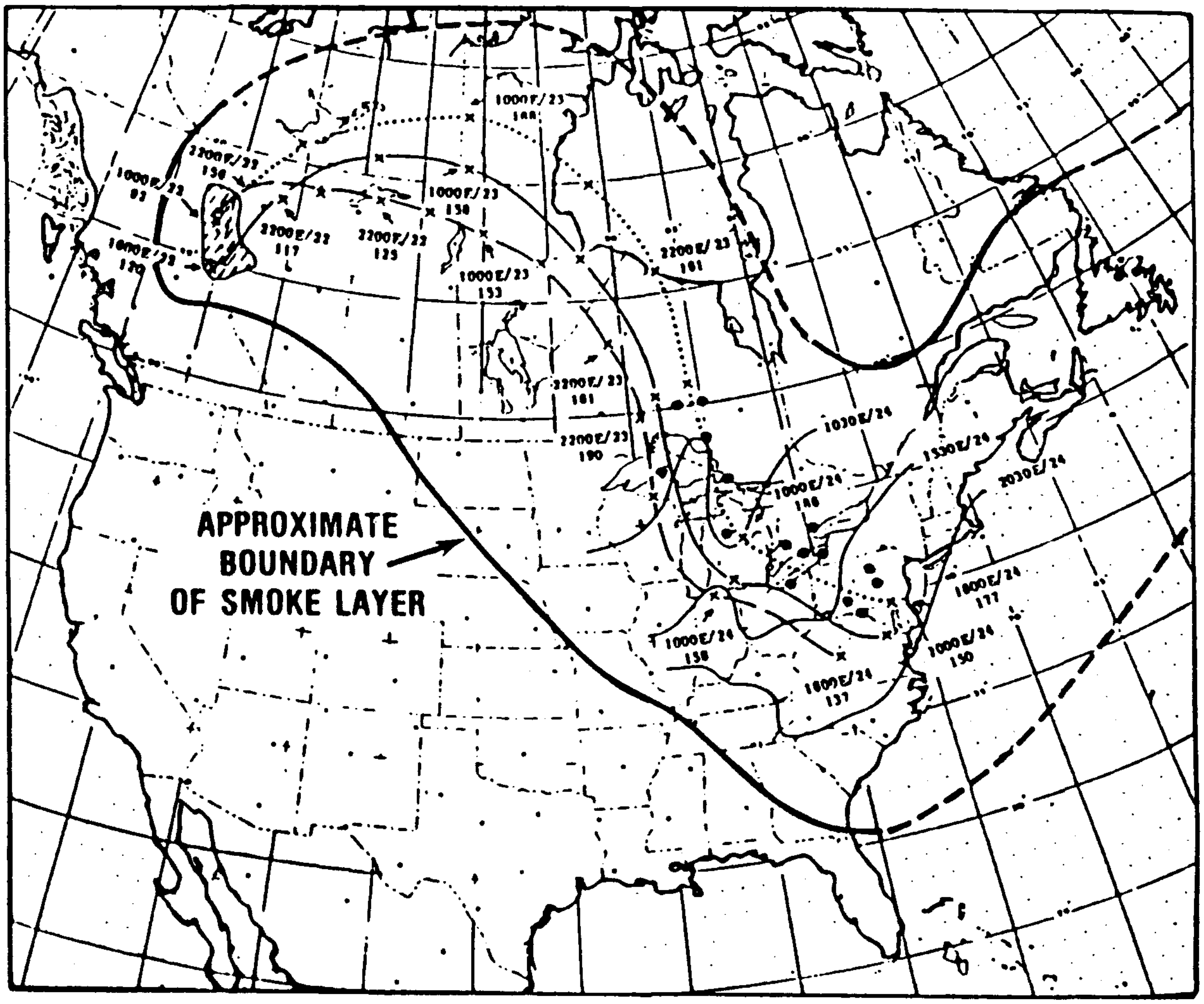

Figure 2. Canadian Smoke Plume

Table 6 describes the Tacoa, Venezuela, oil fire, a very large[4] oil fire which could be seen from weather satellites. Here the smoke plume was white, probably as a result of moisture transported up by the smoke plume (cf. Bauer, Albini, and Chandler, 1986; see also the subsequent discussion in Section 3.3).

Table 6. Tacoa Oil Fire, December 1982

• Large oil fire at a storage tank for the main power plant for Caracas, Venezuela.
• The tank caught fire at night--major incident with fatalities.
• Weather Satellite imagery: NOAA Polar Orbiter 8 a.m. satellite saw plume 2 p.m. satellite did not see plume (poor geometry, too many clouds) GOES high-resolution visible saw series of small plumes around noon
• Very moist atmosphere: looked like white cloud, mainly water
• Contrast with a fire at an oil refinery in Long Beach, CA, in May 1958--black plume • At Long Beach, CA, in May the atmosphere is quite dry. • Atmospheric moisture at different locations (specific humidity at surface at 10 a.m. local time, g/kg, from Oort, 1983): Arctic, spring (60°N) 4 S. France 5-8 Long Beach, CA, May 8 Kuwait, February 6 (Winter); 10 (Summer) Caracas, Venezuela, December 16
• Comparison of white/black clouds versus atmospheric moisture suggests that since the METEOTRON in S. France sometimes produces white clouds, possibly so would the Kuwaiti oil fires, by the same mechanism.

4 Large for an oil fire--but note how much smaller this was than the Kuwaiti oil fires! Tacoa represented a single, concentrated source, and thus the plume rose much higher than the multiple spaced plumes in Kuwait.

3.0 FIRE PLUME PHENOMENOLOGY

3.1 FIRE ENERGETICS AND CHEMISTRY

Wood is basically carbohydrate--$(CH_2O)_x$--while oil can be described as a hydrocarbon--$(CH_2)_y$. All these materials burn with atmospheric oxygen to produce H_2O, CO_2, and CO. Table 7 part A indicates the overall energetics of combustion: 1 kg of fuel requires the oxygen from 5-20 kg of air for combustion, and yields ~4 kt energy/kt wood or 12 kt energy/kt oil for complete combustion.[5]

Normal combustion is not quite complete, so that a variety of products of incomplete combustion including soot are formed. Table 7 part B indicates the representative products of actual combustion per kg fuel including smoke.

3.2 THE RISE OF INDIVIDUAL FIRE PLUMES

The more energetic a given source of combustion, the higher in the atmosphere will its smoke plume rise. A simple analysis of Morton, Taylor, and Turner, 1956, for the rise height h_p of a "small" source (small in horizontal extent relative to the atmospheric scale height)[6]

$$H_o = kT/Mg \sim 7 \text{ km} \quad (1)$$

of uniform power production Q (KW) in an atmosphere of constant lapse rate gives the rise height as

$$h_p \text{ (m)} = 46\ Q^{1/4} \quad (2)$$

This neglects the entrainment of air or atmospheric moisture and the detrainment and deposition of smoke and other combustion products; see, e.g., Griggs, 1969, for a summary of plume rise formulas taking into account various physically significant factors.

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5 1 kt energy = 10^{12} g calories = 4.2×10^{12} joule = 1.2×10^6 kWh; 1 kt mass = 10^3 metric tons.

6 k = Boltzmann's constant, T = temperature; M = average mass per air molecule, g = acceleration due to gravity.

Table 7. Fire and Smoke Phenomenology

A. Combustion Energetics

- 1 kg fuel (wood or oil) + 10 kg air (factor 2) =>1 kg H_2O + 8 kt energy/kt fuel[a]
- Also CO_2 and smoke--see below
- Rising plume entrains lots of air (100-1,000 kg/kg fuel) and lots of water vapor (1-10 kg/kg fuel)

B. Overall Combustion Products for 1 kg fuel (wood, oil, plastic)

- 1 kg H_2O of combustion
- 1-1.5 kg CO_2
- 0.1-0.2 kg CO
- 0.1-0.2 kg smoke: acetylene and other hydrocarbons
  "volatile organic compounds"
  "brown tarry goop"
- 10-30 g graphitic soot (if C/H ~ 1/1)[b]

a 1 kt energy = 10^{12} g calories = 4.2×10^{12} joule = 1.2×10^6 kWh; 1 kt mass = 10^6 kg. Heat of combustion is 4 kt energy/kt fuel for wood, 12 for oil.

b This may be too high--under current examination. (P. Janota)

Current estimates are that 1.5-7 million barrels (Mbbl) of oil are burning per day in Kuwait from some 500-odd wells. Assuming that 5 Mbbl burn per day from 500 wells gives an average power production per well[7]

$$Q_{av} = 560{,}000 \text{ kW} \tag{3a}$$

so that the mean plume rise height from Morton, Taylor, and Turner, 1956, is

$$h_{p,av} = 1{,}300 \text{ m } (4{,}100 \text{ ft}) \quad , \tag{3b}$$

which is not inconsistent with the actual plume heights that are observed.[8]

In comparison with the Tacoa, Venezuela, oil fire discussed in Table 6, note that this was a single, concentrated fire source whose plume rose much higher, i.e., into a

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7 1 bbl oil = 250 lb, mean heat of combustion of oil = 21,000 BTU/lb =11.5 kcal/g.

8 For the illustration of the Dresden Firestorm cited in Section 2, the average power production is 4.4 × 108 kW, corresponding to a plume rise height of 6.6 km, i.e., the smoke plume rises moderately close to the tropopause.

much cooler ambient atmosphere, so that there was a great deal of condensation of entrained moisture. By contrast, the 500-odd fires in Kuwait are individually much smaller and rise only into the relatively warm lower atmosphere so that there would be significantly less condensation, even though the moisture fraction may be similar, at least for the coastal wells. Note that the effects of ground water intrusion into the oil field and thus into the smoke plume, and of possible salt in the (hygrophilic) soot particles, are not discussed here.

3.3 BLACK VS. WHITE SMOKE PLUME[9]

Figure 3--sketched from Space Shuttle photography of land clearing associated with the modern large scale form of slash-and-burn agriculture in Brazil[10]--shows that "small" and "large" fires may behave differently. A small fire simply produces a uniformly expanding grey smoke plume, while a large fire may produce a white cumulus cloud which evaporates later.[11]

If the heat source is large enough, it builds up convection, and if the lower atmosphere is sufficiently moist and the temperature falls off sufficiently rapidly with height, the rising fire plume can entrain 1-10 kg H_2O per kg fuel. As the plume expands, it cools and eventually the humidity may rise above the saturation level for water vapor (which depends strongly on temperature) so that the moisture condenses to form a cloud. Later on the plume expands further and falls below saturation and thus the cloud evaporates again, leaving the grey/black smoke plume. This process is well demonstrated in Fig. 3.

This capping phenomenon has been observed occasionally with the METEOTRON,[12] and indeed it has been observed with the Kuwaiti oil fires, where some of the water in the cloud may also come from ground water intrusion into the oil field.

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9 Aircraft sampling of the Kuwaiti fire plumes by University of Washington shows a high sodium chloride and calcium carbonate content of at least some of the smoke plumes which is said to explain why they are white. Nevertheless, there have been observations in Kuwait of capping cumulus clouds.

10 Slash-and-burn agriculture in the humid tropics consists of cutting trees and/or brush, letting the material dry, and then burning it at the end of the dry season. The ash makes for good crops for 1-3 years, but then the land should be left for 20 years or more to regain its tree cover and fertility. Small-scale operations involve leaving the largest trees which protect the soil from heavy rain which can destroy the soil structure by "laterization." Modern, large-scale techniques, such as dragging a heavy anchor chain between two of the largest size bulldozers to create a large swath (~100-m wide) of downed trees, destroys the protective tree cover and leads to erosion and permanent soil destruction.

11 Upon occasion there is heavy rain from this induced cumulus cloud.

12 The METEOTRON--cf. Church et al., 1980, Radke et al., 1980,1990--was an array (located in southern France) of about 100 oil burners of total power production 1 GW designed to study plume (continued)

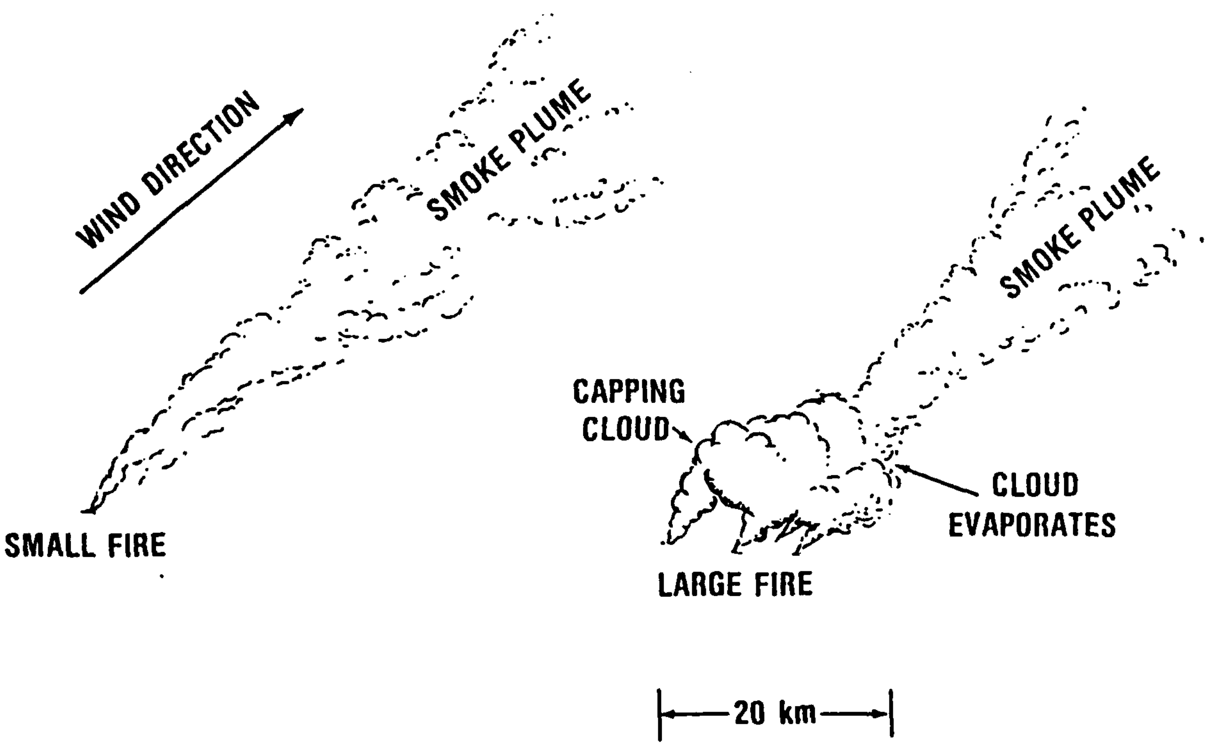

Figure 3. Black vs. White Smoke From Land Clearing by Burning In Brazil

Note that if the lower atmosphere is dry (e.g., over the desert[13] or in the Arctic) there will be no condensation, and so the grey/black smoke plume remains.

The amount and type of smoke is quite different in these two cases:

- Black smoke is treated as soot, 10-30 g/kg fuel, mean particle size 0.01-0.1 μm (see, e.g., Fig. 4 for a representative particle size distribution).
- White smoke is treated as "dirty water" (see Section 5.3 and Table 9; there may be up to 1-10 kg/kg fuel, particle size ~1 μm, as for regular water clouds.

For definiteness, here we treat black smoke as spheres of radius 0.1 μm. This is surely not correct, as most oil fire soot is filamentary or lacy rather than spherical; the assumption is made purely for order-of-magnitude estimates. Figure 4 shows a "representative" soot particle size distribution. Again, we treat the mass of white smoke

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injection into the atmosphere. The average power production of the Kuwaiti oil fires is ~0.6 GW, which is large enough to show similar effects.

13 But note that the Kuwaiti oil fields are located close to the very warm and humid Arabian Gulf, so that if there is a sea breeze (as normally occurs in the daytime), the low-lying atmosphere over the fires will be quite moist.

per kg fuel as 10 times larger[14] than the mass of "black" smoke per kg fuel, and made up of spheres of radius 1 μm.

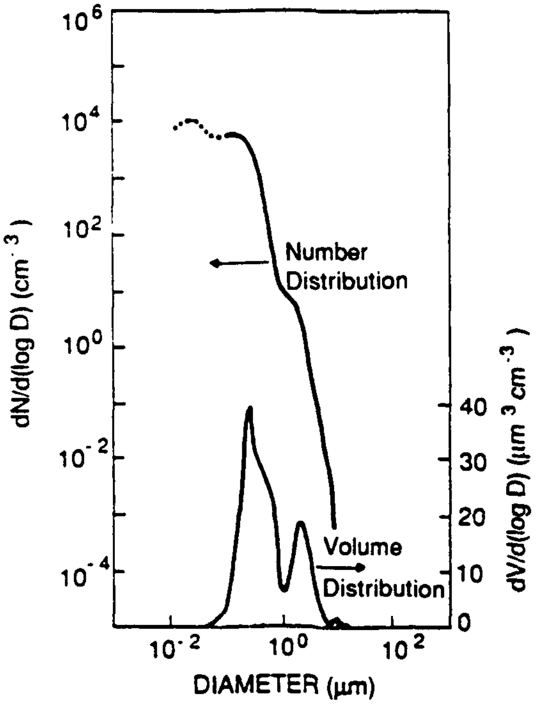

Figure 4. Representative Soot Particle Size Distribution (Source: L.F. Radke, et al., 1990)

Next, let us present some data on mesoscale (< 100 km) atmospheric motions.

14 The mass of "white" smoke due to turbulent entrainment may be a factor of 10 larger than this, i.e., 100 times that of "black" smoke. Ground water intrusion could also increase the amount of water in white smoke.

4.0 MESOSCALE METEOROLOGY AND ATMOSPHERIC MOTIONS

4.1 PLUME SPREADING

The atmosphere is highly variable, but one can describe average plume/cloud spreading relatively straightforwardly. If the horizontal wind direction defines the x-axis and the z-direction is vertical, there is an extensive collection of data on transverse plume spreading, with the mean cloud width $\sigma_y = \sigma_{trans}$ as indicated in Fig. 5 as a function of travel time--cf. Bauer, 1984b.[15]

The data of Fig. 5 represent the wide range of variability that is characteristic of the atmosphere in turbulent motion. Table 8 lists the scales of atmospheric motions as compiled by Hobbs, 1981, and by Ramage, 1976, who use somewhat different sets of criteria, but reference to Fig. 5 shows that the range of σ_y agrees rather well with the scales of atmospheric variability as represented by ambient atmospheric turbulence. (The more recent compilations of Gifford, 1989, also agree quite well with these data.)

J. Cockayne[16] points out that dispersion data in the 1.5-150 hour and 20-2,000 km region of Fig. 5 represent a regime where current codes need good empirical data for both direct use and parameterization guidance. The very wide range of variability reflects both on the intermittency of atmospheric turbulence and on the distinction between driving and induced (or driven) motions.

For mean longitudinal cloud width (σ_x) and vertical cloud width (σ_z) we may use σ_y with some modifications. Longitudinal spreading can be described in terms of a mean dispersion velocity u_{dis} as

$$\sigma_x = \sigma_{long} = u_{dis}\, t \qquad (4a)$$

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15 Older data based on Hage, 1964, 1966, and quoted in Bauer, 1974, show much smaller spreading, with mean spreading shown in Curve II of Fig. 5 (vs. Curve III) and maximum spreading in Curve III (vs. Curve IV). As has been pointed out by J. Angell, NOAA/ARL, these older data were biased towards quiet (low turbulence) atmospheric conditions, as the old detection techniques were limited in sensitivity, so that when vigorous turbulent motions tore a cloud apart it could no longer be detected.

16 In reviewing this document.

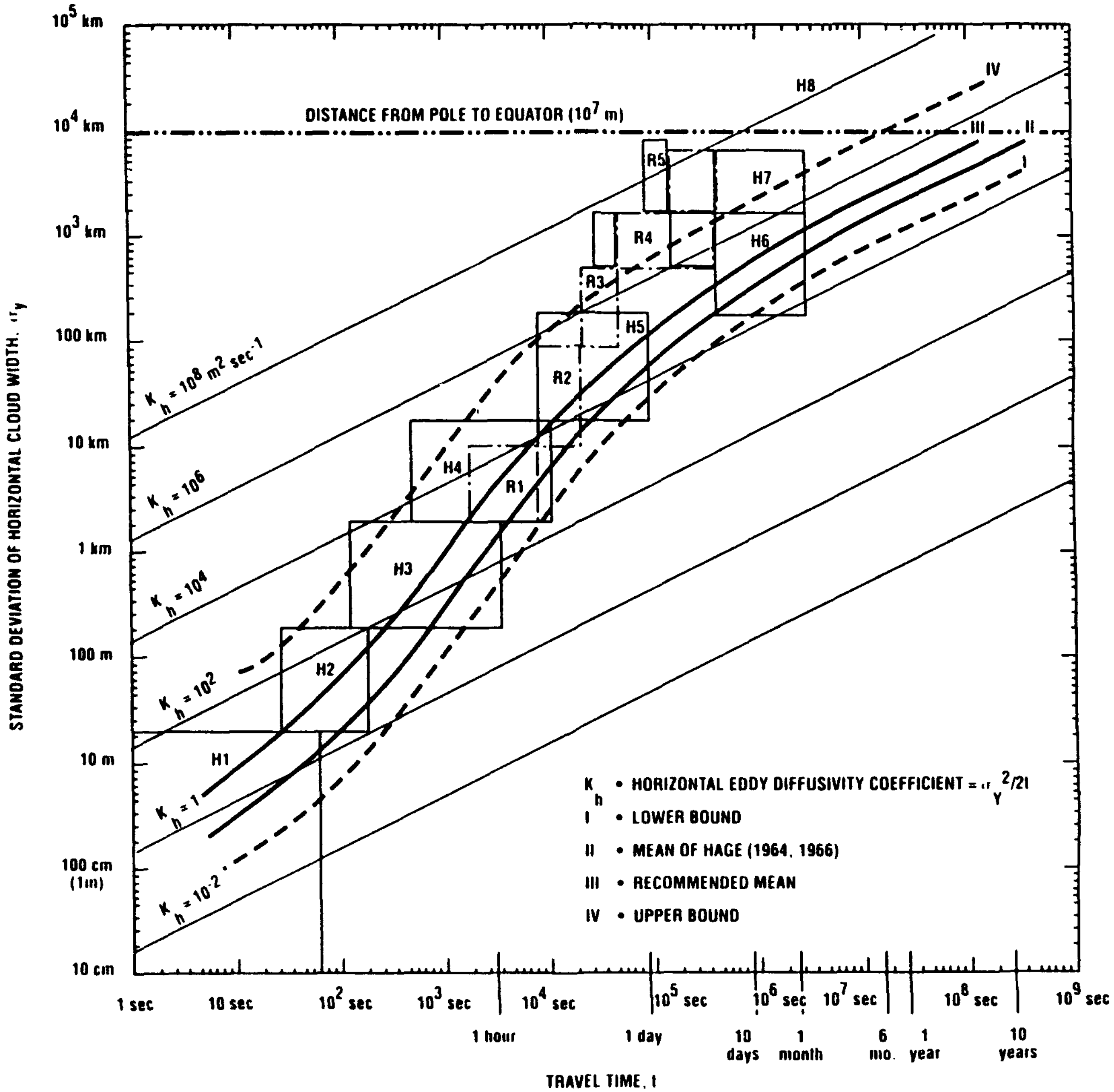

Figure 5. Cloud Spreading: Comparison of Data with the Hage (1964, 1966) Bounds, and with the Representative Scales of Atmospheric Motions Characterized in Table 8 (Source: Bauer, 1984b)

Table 8. Representative Scales of Atmospheric Motions

Region on Fig. 5	Scale	Phenomena	Approximate Affected Scale	
			Horizontal Dimension	Time
(From Hobbs, 1981: Different Atmospheric Motions)				
H1	Micro-γ, δ	Plumes, Mechanical and Isotropic Turbulence	2 mm to 20 m	1 sec to 1 min
H2	Micro-β	Dust Devils, Thermals, Wakes	20 m to 200 m	0.5 min to 3 min
H3	Micro-α	Tornadoes, Deep Convection, Short Gravity Waves	200 m to 2 km	2 min to 1 hr
H4	Meso-γ	Thunderstorms, Internal Gravity Waves, Clear Air Turbulence, Urban Effects	2 to 20 km	6 min to 3 hr
H5	Meso-β	Nocturnal Low-Level Jet, Inertial Waves, Cloud Clusters, Mountain and Lake Disturbances, Rain Bands, Squall Lines	20 to 200 km	2 hr to 1 day
H6	Meso-α	Front Hurricanes	200 km to 2,000 km	5 days to 1 month
H7	Macro-β	Baroclinic Waves	2,000 km to 5,000 km	2 days to 1 month
H8	Macro-α	Standing Waves, Ultra-Long Waves, Tidal Waves	> 10,000 km	> 1 day
(From Ramage, 1976: Turbulence Bursts on Different Scale)				
R1	Convective	Hot Towers	2 km to 10 km	15 min to 2 hr
R2	Mesoscale	Flash Floods	10 km to 100 km	2 hr to 6 hr
R3	Sub-synoptic	Tornadoes, Clear Air Turbulence, etc.	100 km to 500 km	6 hr to 12 hr
R4	Synoptic	Continuous Thunderstorms, Large-Scale Convection	500 km to 2,000 km	12 hr to 48 hr
R5	Planetary	Hurricanes, etc.	2,000 km	24 hr to 48 hr

and we may perhaps take u_{dis} as some fraction of the horizontal advection speed, u_{ad}, which we take as 30 km/hr. Thus here we use the following numerical values:

$$u_{ad} = 30 \text{ km/hr}; \qquad u_{dis} = u_{ad}/2 = \qquad 15 \text{ km/hr}. \tag{4b}$$

Vertical cloud spreading is limited as a result of gravity: a simple model is

$$\sigma_{vert} = \begin{cases} \sigma_{trans}(t) & \text{for } \sigma_{trans} < \sigma_1 \\ \sigma_1 & \text{otherwise} \end{cases} \tag{5}$$

where $\sigma_1 \sim H_o/2$, H_o = scale height, ~ 7 km.

4.2 PLUME RISE AND MIXING IN THE MESOSCALE

From the discussion of Section 3.2 of the plume rise of isolated individual plumes, it seems that most of the smoke rises above the planetary boundary layer so that it can enter the free troposphere. In fact, the fires are too far apart to form one large convection column but too close together to form separate plumes in the troposphere.[17] This makes it difficult to draw direct conclusions from observations, while at the same time limiting the global influence because of the relatively low altitude of the smoke injection.

For definiteness, we assume that all the smoke mixes (uniformly!) into a tropospheric mesoscale air mass. Suppose that this air mass has a transverse dimension of 100 km and the advection speed u_{ad} = 30 km/hr as in Eq.(4b), so that with an atmospheric scale height H_o = 7 km, the mass of air which absorbs the 45,000 tons of (black) smoke per day (see Table 1) is

$$\begin{aligned} M_{t,meso} &= 1.2 \text{ kg/m}^3 \times 100 \text{ km} \times 30 \text{ km/hr} \times 24 \text{ hr} \times 7 \text{ km} \times 10^9 \text{ m}^3 \\ &= 6 \times 10^{14} \text{ kg/day}. \end{aligned} \tag{6}$$

The heat of combustion per day of these oil fires is comparable to the total heat of combustion of a large forest fire (e.g., item FF of Table 1). This is part of the additional energy input into the mesoscale air mass containing smoke. There will be additional heating due to the absorption of sunlight and earthshine by the cloud of smoke particles, and also cooling due to the radiation from the optically thick cloud. Numerical estimates of

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[17] The lack of low-level interaction of the individual well fires is indicated by the lack (or scarcity) of fire whirls reported.

this heating follow, on the assumption[18] that the smoke cloud is optically thick at all wavelengths of importance.

If all the heat of combustion of the 5 Mbbl/day that is burned goes into this mass $M_{t,meso}$, this corresponds to an energy of 4.2×10^{16} joule which leads to a temperature rise of 0.075 K. This should be compared with the maximum solar energy that can be absorbed by this air mass if it is optically thick, which is 4.4×10^{18} joule/day and corresponds to a net heating rate of 8 K/day. Representative measures[19] of the rate of energy gain due to earthshine is 0.22 K/day and the daily radiative cooling is 0.27 K/day.

Note that the air mass associated with a large forest fire will tend to be very warm, i.e., have a high potential temperature, because it is this warm air that has dried out the forest to the point that serious fires can occur. An air mass of high potential temperature tends to rise towards the tropopause, as was observed in the case of the 1950 Canadian forest fires discussed in Table 5 and Fig. 2. Presumably forest fire meteorologists have studied the behavior of this kind of air mass.[20] By contrast, the air over Kuwait will have a more normal distribution in potential temperature, etc., so that the air mass will be less likely to rise to the tropopause, and thus will retain its identity for only perhaps 3-10 days. It is thus not likely that the smoke from the Kuwaiti oil fires will have a global climatic effect.

4.3 NUMERICAL ANALYSIS OF MESOSCALE MOTIONS

The description of Fig. 5 is a very simple time-averaged model, representing atmospheric cloud spreading as either fast (Curve IV), slow (Curve III), or very slow (Curve I). Indeed, the discussion given here presents plausible orders of magnitudes and simple physical effects without a detailed discussion which would require a very large amount of specific input data.

Reference to Fig. 1 shows that the wind direction--and presumably also the wind speed--can vary significantly from day to day, as well as between day and night and on shorter time scales. Given specific data on the wind speed, temperature, and pressure as a function of space and time, one can compute the atmospheric motions numerically, by

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18 Which--according to P. Janota--is not true in the LWIR.

19 We treat the earth as a black body at T = 300 K and the plume as a black body at T = 270 K.

20 Forest fires are typically wind-driven, with the greatest heat release at the front, feeding the air column that has passed over the fire, so even large forest fires make one or two large convection columns--not many small ones that merge much later (and higher) as they spread.

using mesoscale models such as those of Douglas Fox, USFS, Ft. Collins, Colo., or Paegle and McLawhorn, 1983; see also Berri and Paegle, 1990.

A broadly applicable model has been prepared by TASC, see Chase et al., 1991. This model is intended to provide information for health and environmental assessment applications. The inputs come from available NOAA predictions or climatology when there are no data.

I have not seen a comparison between any model predictions and detailed observations, but understand (from the reviewers) that agreement is frequently not good.

There is certainly a major change in wind direction, temperature, and humidity between winter and summer which will affect both the atmospheric motions and also possibly the applicability of the different models. A particular problem which arises in and near the Gulf is "Aziab weather," shallow-pressure movements in Saudi Arabia associated with the dust storms that are rather prevalent during the spring season in the Arabian Gulf (see Siraj, 1980).

5.0 OPTICAL OBSCURANTS AND THE DETECTION OF TARGETS AND CLOUDS

5.1 DIMENSIONLESS OPTICAL THICKNESS

For the problem of the obscuration of a ground target by a smoke (or other) cloud, it is convenient to define a Dimensionless Optical Thickness for Extinction,

$$X_{ext} = n\,(\sigma_{abs} + \sigma_{sca})\,L \tag{7}$$

where:

L = geometrical thickness of cloud in viewing direction [we take $L = 7$ km $= H_0$ of Eq.(1)]

n = number of particles per unit volume averaged over L

σ_{abs} = absorption cross section; σ_{sca} = scattering cross section

$\sigma_{ext} = \sigma_{abs} + \sigma_{sca}$, extinction cross section.

5.2 DETECTING A TARGET IN PRESENCE OF A CLOUD

This depends both on the wavelength and on the details of the sensing system. Thus in the visible and near-IR a target is detected largely by reflected sunlight, while in the MWIR and LWIR the biggest contribution to the target signature comes from its thermal emission. The cloud itself produces several distinct effects on an underlying target:

1. It attenuates the signal from the target (crudely, by a factor e^{-X}).
2. It changes the background and thus the contrast.
3. If there is any significant scattering, the beam is broadened so that the signal from the target is spread out and thus the contrast is reduced.
4. Finally, if the cloud is non-uniform, the target can sometimes be seen and sometimes not.

Without going through these details, it is reasonable to say that if the optical thickness X is greater than ~ 4, so that the transmission is < 2%, the meteorological definition of visibility, the target will be obscured, and this assumption will be made here.

5.3 SCATTERING PROPERTIES OF SMOKE PARTICLES: EXTINCTION CROSS SECTIONS FROM MIE THEORY (VAN DE HULST, 1957)

For a medium of complex refractive index $N = N_1 - i\, N_2$, with Mie parameter

$$q = 2\, \pi a/\lambda \tag{8}$$

where a = particle radius and λ = wavelength of radiation, we have (cf., e.g., Van de Hulst, 1957):

If $q \ll 1$

$$\sigma_{abs} \sim (8/3)\, \pi\, a^2\, q\, N_2 \text{, proportional to particle volume} \tag{9a}$$

$$\sigma_{sca} \sim \pi\, a^2\, (N_1-1)^2\, q^4 \text{, i.e., very small} \tag{9b}$$

If $q \sim 1$

$$\sigma_{abs} \sim N_2\, \pi a^2 \tag{10a}$$

$$\sigma_{sca} \sim \pi a^2 \tag{10b}$$

If $q \gg 1$

$$\sigma_{abs} \sim \pi a^2, \text{ if } N_2 q \gg 1 \tag{11a}$$

$$\sigma_{sca} \sim \pi a^2 \tag{11b}$$

5.4 SEEING A CLOUD

Next we ask for the detection of a cloud by overhead surveillance from space:

- In Visible: a cloud can be detected if $X_{ext} > 0.03$ (R.S.Fraser, NASA)
- In MWIR: 3.5 µm goes through the smoke plume from a wood fire, sees hot spots on ground (M.Matson, NOAA)
- In LWIR: at 11 µm a cloud can be detected if $X_{ext} > 0.1$ or so.[21]

We shall assume that a cloud can be detected at any wavelengths if $X_{ext} > 0.1$.

[21] Reference to Table 9 suggests that cloud optical thickness is frequently larger in the visible than in the LWIR, and thus presumably clouds are normally easier to detect in the Visible than in the LWIR. P. Janota reports that the black (soot) clouds over Kuwait are essentially transparent in the LWIR.

6.0 PHENOMENOLOGY--CONTINUED

6.1 PEAK OPTICAL THICKNESS OF SMOKE PLUME

The volume of the mesoscale air mass of Section 4.2 is 5×10^{14} m^3/day, and assuming that all the smoke is uniformly mixed in the air mass, the number density of (black) smoke particles is ~ 2×10^7 cm^{-3} (if a = 0.01 μm) or ~ 2×10^4 cm^{-3} (if a = 0.1 μm), or ~ 200 cm^{-3} for white smoke particles, where a = mean smoke particle radius, and we assume that:

a = 1 μm for "white" smoke, and

mass of "white" smoke = 10 × mass of "black" smoke.

Numerical values for the complex index of refraction of "soot" and "dirty water" in the Visible (0.5 μm), MWIR (3.75 μm), and LWIR (11 μm) are cited in Table 9, where we also show σ_{abs} and σ_{sca} and the peak optical thickness X_{ext} for "black" and "white" smoke (defined in Section 5.1).

Using the cross section numbers from Table 9, the extinction optical thickness assuming uniform mixing of the injected black smoke with the mesoscale air mass of 6×10^{14} kg/day and L = 7 km = atmospheric scale height, is 6.3 in the visible and 0.49 in the LWIR, for both 0.01 and 0.1 μm mean smoke particles. For white smoke the optical thickness is much larger (see Table 9).

In the following Section we use the representative measures of cloud spreading due to ambient atmospheric turbulence from Section 4.1 to estimate how rapidly the smoke number density decreases so that the plume optical thickness in vertical viewing falls below the threshold of detection.

6.2 PLUME SPREADING AND DISAPPEARANCE

From the discussion of Section 5.2, a target can be seen beneath a plume if $X_{ext} < X_{crit} \sim 4$, and a plume can be detected against an earth background if $X > 0.1$ or so.

Table 9. Numbers for Different Kinds of Smoke

- Spherical particles of radius a, made up of medium of complex refractive index $N_1 - iN_2$ with Mie parameter $q = 2\pi a/\lambda$, from Van de Hulst, 1957 (λ = wavelength of radiation).
- Typical numerical values (see Jursa, 1985, p. 18-17 for refractive index data)
- We assume that (mass of white smoke) = 10 × (mass of black smoke)--could be larger by another factor of 10.

Wavelength	VIS (0.5 μm)	MWIR (3.75 μm)	LWIR (11 μm)
Black Smoke--Soot, a = 0.1 μm			
Complex Refractive Index $N_1 - i\,N_2$	1.75 – i 0.45	1.90 – i 0.57	2.23 – i 0.73
$q = 2\pi a/\lambda$	1.2	0.17	0.057
$\sigma_{ext} = \sigma_{abs} + \sigma_{sca}$	4.5×10^{-10} cm^2	8.1×10^{-11} cm^2	3.5×10^{-11} cm^2
X_{ext} (t_m)	6.3	1.1	0.49
White smoke--Dirty Water, a = 1.0 μm			
Complex Refractive Index $N_1 - i\,N_2$	1.5 – i 0.01	1.37 – i 0.004	1.6 – i 0.2
$q = 2\pi a/\lambda$	11	1.7	0.6
$\sigma_{ext} = \sigma_{abs} + \sigma_{sca}$	9.5×10^{-8} cm^2	9.4×10^{-8} cm^2	$(5 \times 10^{-10} + 1.5 \times 10^{-9})$ cm^2
X_{ext} (t_m)	13	13	0.28

The optical thickness has a maximum when the smoke is entrained in a mesoscale air mass, then decreases with time as the particle number density n decreases.

Smoke number density,

$$n \sim 1/\text{volume of air mass, i.e., } \sim 1/(\sigma_{trans} \times \sigma_{long} \times \sigma_{vert}) \qquad (12)$$

where here the σ's are mean cloud widths:

- From Section 4.2 we start with σ_{trans} = 100 km, which corresponds to the following times t_m:
  - For Fast Spreading (curve IV of Fig. 5) this corresponds to t_m = 1.5 hr.
  - For Mean Spreading (curve III) t_m = 25 hours
  - For Slow Spreading (curve I) t_m = 125 hours (5.2 days)

From Section 4.2, Eq. (4), $\sigma_{long} \sim u_{dis} \times$ time ; $u_{dis} \sim 15$ km/hr ($= u_{ad}/2$) and $\sigma_{vert} \sim$ const ~ 7 km. Thus the smoke can be uniformly spread in a 24 hour time period for Fast or Mean spreading (levels of turbulence), not for Slow spreading.

As time increases by factor (t/t_m) over t_m, X_{ext} decreases by a factor $\sim (t/t_m)^{-g}$, $g \sim 1.7$ (for $\sigma_{trans} > 100$ km for curves I, III, IV), so that for an initial $X_{ext} = 6.3$ or 13 (see Table 9) we go to 0.1, down by a factor 63 or 130, by going to $\sim 11\ t_m$ or $17\ t_m$, respectively. Table 10 shows how the optical thickness and thus obscuration by the smoke cloud falls off with time under different conditions. In essence X_{ext} decreases quite rapidly with increasing time, so that the smoke cloud disappears simply because its density falls below the threshold for detection, even in the absence of any physical removal or destruction mechanism for the smoke particles.

Table 10. Plume Spreading and Disappearance

- For transverse distance $\sigma_y = 100$ km
- Characteristic mixing time t_m=
  - 1.5 hours for fast spreading (Curve IV of Fig.5)
  - 25 hours for mean spreading (Curve III)
  - 130 hours for slow spreading (Curve I)

- Maximum Numbers:

	Visible	MWIR (3.75 µm)	LWIR (11 µm)
Black Smoke X(max)	6.3	1.1	0.49
Target obscured to	1.3 t_m	No Target Obscuration	—
Cloud can be seen to*	11 t_m	4 t_m	2.5 t_m
White Smoke X(max)	13	13	0.28
Target obscured to	2 t_m	2 t_m	-
Cloud can be seen to*	17 t_m	17 t_m	1.8t_m

* Water may evaporate, i.e., cloud may disappear sooner.

For obscuration of a target by a cloud rather than detection of the cloud, we may require $X_{ext} > 4$, so that with an initial peak value of $X_{ext} = 10 \times 13$ for white smoke (where the factor 10 corresponds to the maximum amount of white smoke, see Section 3.3), the target would remain obscured up to $\sim 8\ t_m$.

None of these numbers are firm, but they do give an indication of the wide range of quantitative results that one can expect.

6.3 RAINOUT OF SMOKE

There have been references to black, oily rain in Kuwait. Some representative numbers on how fast the material will rain out can be obtained from a standard precipitation scavenging rate, $\Lambda_{ref} = 10^{-4} - 10^{-3}$ sec^{-1}, i.e., $1/\Lambda_{ref} = 17$ min. – 3 hours. (cf. Makhon'ko and Malakhov, 1974). (After time t, the fraction of initial material remaining as smoke is $\exp - \Lambda_{ref}\, t$).

Note:	Λ_{ref}	applies to aerosols in cloud;		
		for aerosols below cloud,	use	$\Lambda_{ref}/10$
		for gases in cloud,	use	$\Lambda_{ref}/10$
		for gases below cloud,	use	$\Lambda_{ref}/100$
		for heavy (convective) rain,	use	Λ_{ref}
		for drizzle,	use	$\Lambda_{ref}/10$.

The numbers are quite variable: they depend on physical and chemical properties of the particles and on the ambient atmospheric conditions. If it rains respectively for 1 hour or for 24 hours, the fraction of the initially injected smoke remaining is the following as a function of Λ:

	Duration of rain: 1 hour	24 hours
$\Lambda = 10^{-5}$ sec^{-1}	0.96	0.42
10^{-4}	0.70	2.7×10^{-2}
10^{-3}	3×10^{-2}	3×10^{-38}

7.0 DISCUSSION

7.1 NOTE THAT:

- The Kuwaiti oil fire plumes are quite inhomogeneous, consisting of a variable mixture of black and white smoke and of oil droplets.
- Meteorological conditions vary both regularly and at random: there is always a sea breeze off the Gulf in the daytime as contrasted with a land breeze off the desert at night; the "rainy season" is in winter, while in summer it is dry and very hot. Especially in spring there are occasional dust storms associated with shallow low pressure systems ("Aziab weather"--see Siraj, 1980).
- Estimates of the oil combustion rate during April-June 1991 vary from 1.5 to 7 Mbbl/day.
- The number of wells burning varies. Some fires are put out, but if a well cannot be capped, the oil jet has been relit to minimize the accumulation of unburned oil on the surface, which leads to the formation of large pools of oil.
- As of October 1991, estimates suggest that most of the fires will be extinguished by late 1991.
- A large number of measurements have been made; some measurements and in particular the analysis of experimental observations are ongoing; so far very few of the results have been analyzed and reported.

Local ground or airborne observations would be expected to be highly variable in space and time because of the variability and inhomogeneity of conditions over Kuwait. These non-uniformities will tend to make any results very difficult to interpret. Measurements at large distances and long times are difficult to make[22] and to interpret and material published to date (October 1991) tends to be highly variable and anecdotal--cf., e.g., Limaye et al., 1991.

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[22] Kaufman, Fraser, and Ferrare, 1990, have developed a methodology for using multispectral data from the AVHRR sensor on the NOAA polar orbiting weather satellites to determine the cloud optical thickness (over the range 0.1 to 2.0), single scattering albedo, and mean particle radius. This technique requires some calibration and validation, but has the potential of providing extensive data at very modest cost. However, it appears not to work for absorbing as distinct from scattering particles, and AVHRR data over land surfaces are hard to interpret, especially for small cloud optical thicknesses.

However, over the next several years there will appear detailed reports and analyses of the many flight and other measurements that have been made. Thus, for example, at the American Geophysical Union Meeting in San Francisco in December 1991 there will be several sessions of contributed papers, possibly 50 in all, and a number of different technical meetings will cover this area during the next several years.

Reference should be made to the TASC numerical assessment model (Chase et al., 1991) which will be useful for an appropriate application, although it must be verified by comparison with detailed measurements.

7.2 CONCLUSION

The fires are clearly a major environmental disaster, and there will be surface cooling in the immediate region of Kuwait. Most of the smoke will not rise above the middle troposphere so, while there may be regional effects, there are unlikely to be any global climatic effects.[23]

Because of the extreme variability of the *local effects* [wind direction and speed and character of the smoke--black (soot) vs. white (dirty water or salts) vs. oil droplets] it is difficult to learn much from local sampling experiments. However, local sampling--mainly airborne--has found large quantities of salts (mainly NaCl and $CaCO_3$), and also finds the soot particles to be surprisingly hygrophilic (which may possibly be due to the extensive presence of salts in atmospheric aerosols). The soot emission factor is much less than the original prediction, and surprisingly little SO_2 has been found to date.

At large distances (> 1,000 km) there have been occasional sightings of smoke either from satellites or from ground observations, but many early reports are largely anecdotal or qualitative--see, e.g., Limaye et al., 1991, Lulla and Helfert, 1991.

An operational problem would be the detection of targets from overhead sensors looking through the smoke plume. Here it is the variability and "fractal" structure of the plumes that needs to be understood because it can teach us how to sample through plumes to increase the probability of a successful look.

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23 A mesoscale air mass which contains the smoke from the fires typically retains its integrity for times on the order of 3-10 days in which it travels maybe 1 ,000-3,000 km, producing a regional rather than a global effect. The lifetime of the smoke particles may be somewhat larger (perhaps by a factor of two), but there are most unlikely to be any global climatic effects, which would require the smoke particles to survive in the atmosphere for times of several years.

R. Small[24] points out that many of the trajectory or mesoscale models used to predict plume behavior did very poorly; this event gives us the opportunity to determine why the models fail. Moreover, experimental data of Kuwaiti plumes could lead to the development of entirely new models, and one could go further and devise checks for the Global Circulation Models. In addition, experiments in Kuwait can help us to understand plume dispersion, effects of land-water interfaces as well as phenomena such as self-lofting of plumes, scavenging processes, emission factors, and the optical properties of aerosol clouds.

J. Cockayne[24] enlarges on this, pointing out that dispersion data in the 1.5-150 hour and 20-2,000 km region (see Fig. 5) represent a regime where current codes need good empirical data for both direct use and parameterization guidance. Such data, which can be (and have been) obtained in Kuwait, can help in both fundamental and applied work, both to solidify the recent progress by Gifford, 1989, and earlier, and by others, in the understanding of atmospheric eddies in the mesoscale range to lead to a causal model to replace the statistical approach to dispersion, and also to improve the numerical simulations used by the Joint Strategic Target Planning Staff and other DOD agencies.

P. Janota[24] points out that most of the experts' original predictions regarding key aspects of the fires such as self-lofting and global impacts, the sulfur budget, the soot emission factor, soot as a nucleating agent, and the surface concentrations of smoke have been wrong, and that much more needs to be learned about these factors through detailed measurements and more effective modeling.

From the standpoint of SDIO, the basic physical elements of the fire and smoke phenomenology appear to be understood (with the possible exception of the white salt crystals and the hygrophilic character of the soot in the smoke plume, which may well be related to the fact that atmospheric dust in the Gulf region has a large salt content). What appears to be new and could profitably be investigated is the interaction of these different elements, and in particular how successful the DOD integrated phenomenology models are in describing the total problem involving many fires rather than a single fire. The reviewers' comments cited above indicate specific deficiencies in understanding and models

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24 In reviewing this document.

which can be corrected.[25] Overall it is important that the data taken should be analyzed to the extent that they can verify and improve existing phenomenology models.

This document represents an early look at the smoke plumes before most of the observations have been analyzed, reviewed, and published. Thus its main function is to raise questions that should be addressed more carefully later on, once the initial observations are understood.

7.3 RECOMMENDATIONS

1. Since the fires will very shortly have been extinguished, it is important to archive all existing data, and to analyze them to the extent reasonable.
2. Specific issues to be addressed include the following:

   2.1 hygrophilic soot

   2.2 white smoke--salts?

   2.3 Sulfur budget

   2.4 Soot fraction.

   2.5 Plume self-lofting

   2.6 Plume spreading
3. Check phenomenology codes to see under what conditions they work and when and how they fail.

[25] There is a certain analogy with the nuclear multi-burst problem: given the environment created by a single nuclear burst, it is not trivial to predict a corresponding multi-burst environment.

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